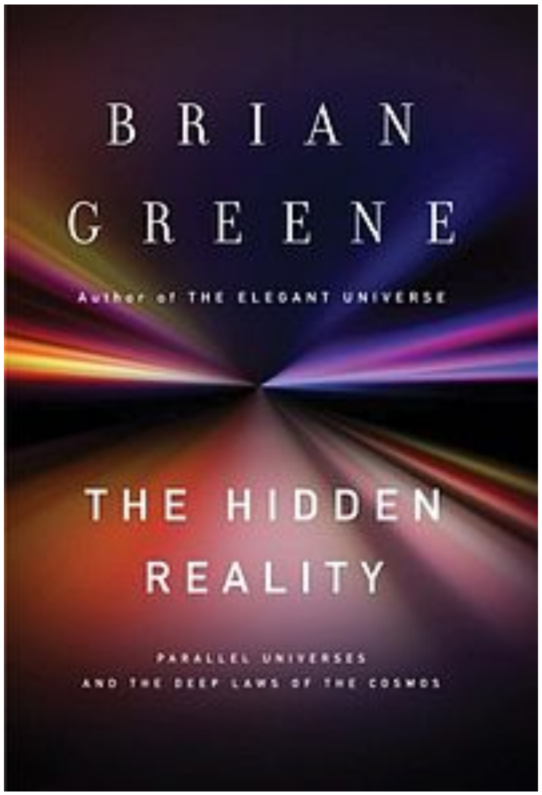
Brian Greene, Nov 6 @ 7pm

Elliott Hall of Music



Free seating pass required for entry

http://www.convocations.org/portfolio/brian-greene-11-6-14/#sthash.KqvAENA9.dpuf

Last Time

- Ohm's Law
- Series and Parallel Resistors
- Series and Parallel Capacitors

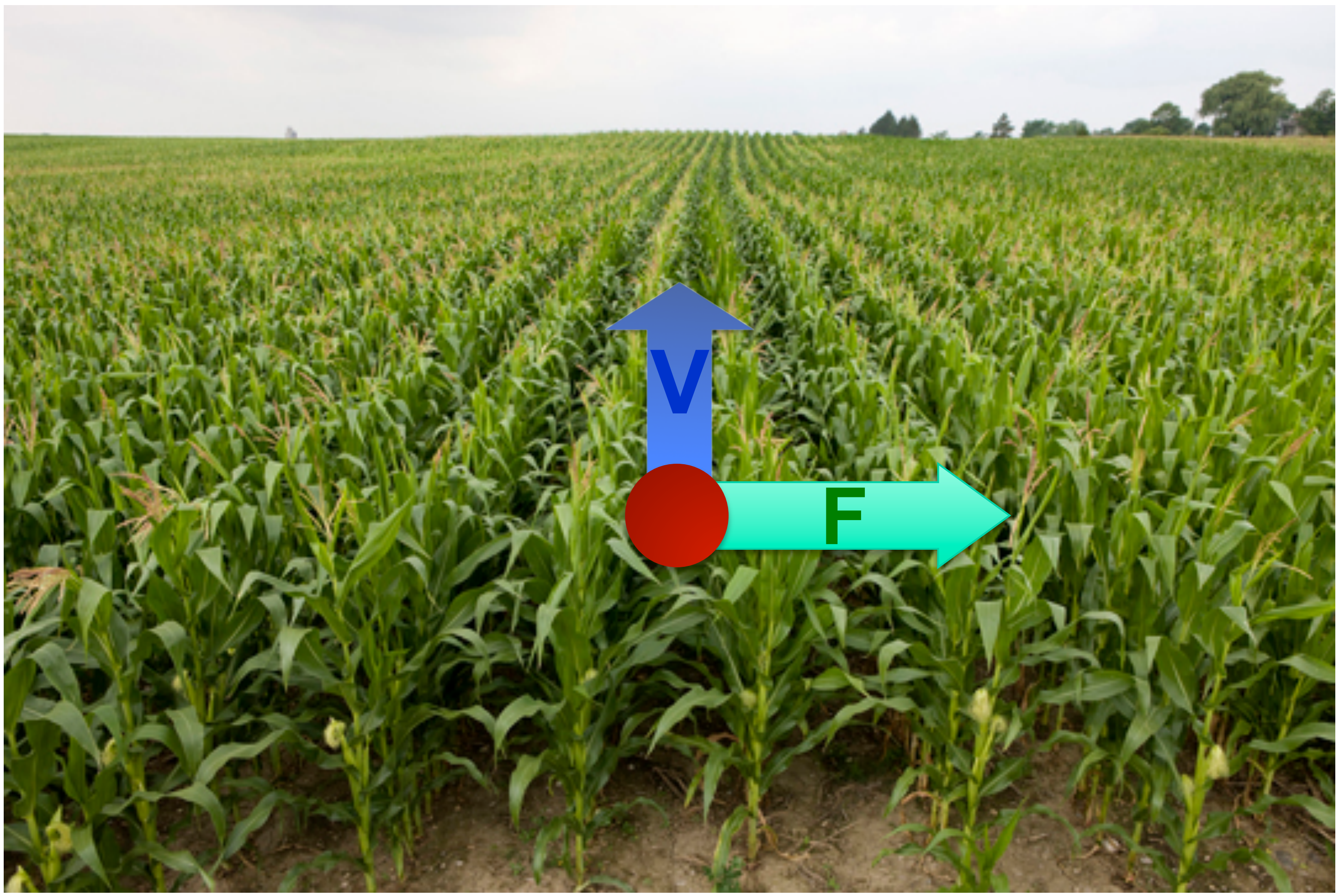
Today

- Ohm's Law
- Series and Parallel Resistors
- Series and Parallel Capacitors

Magnetic Force on a Charge

$$\vec{F}_{magnetic} = q\vec{v} \times \vec{B}$$

A proton walks into a Corn Field/Magnetic Field.
Which way the force point?

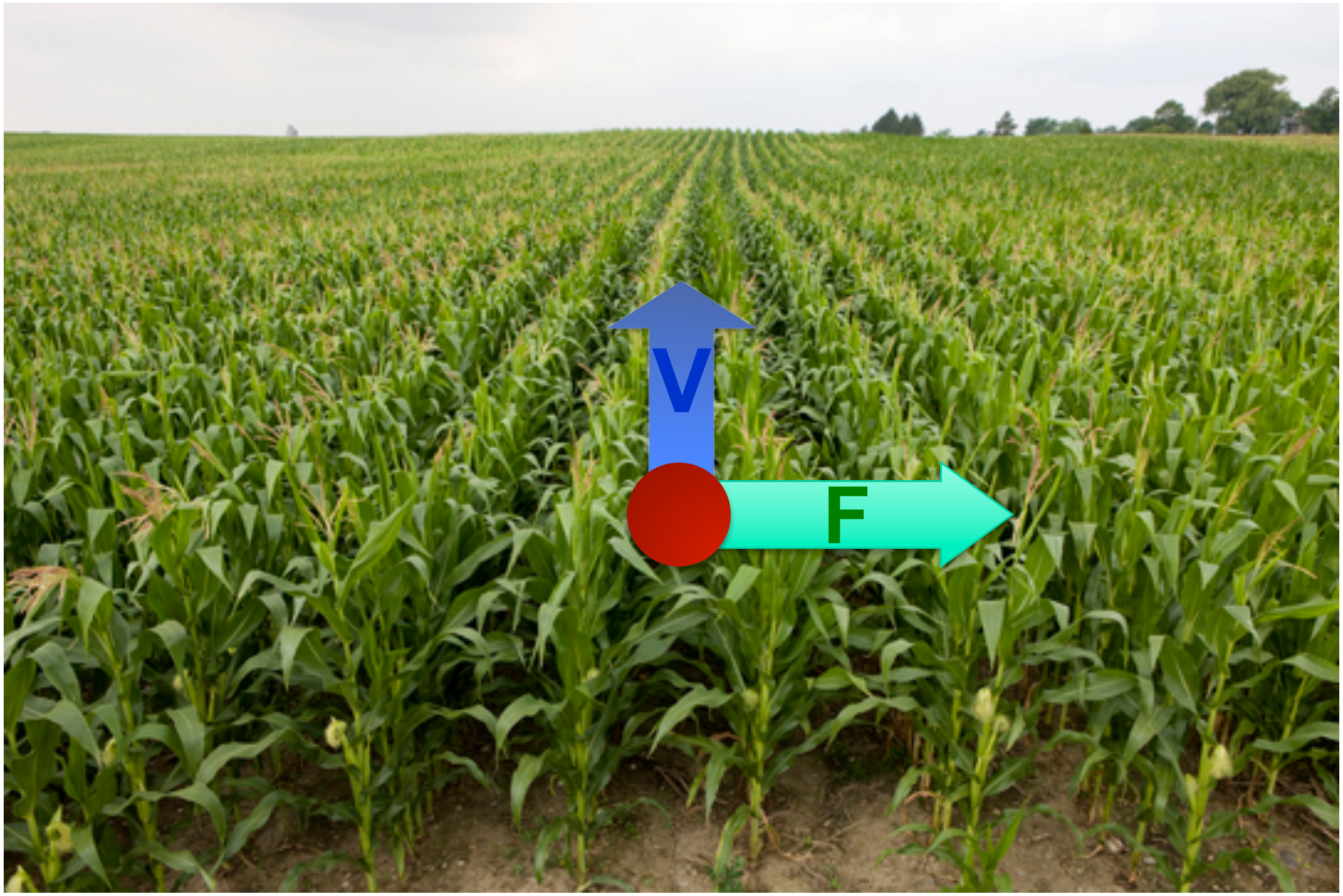


syngenta.com

Magnetic Force on a Charge

$$\vec{F}_{magnetic} = q\vec{v} \times \vec{B}$$

Force ALWAYS perpendicular to velocity.
Where else have you seen this?



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Magnetic Force on a Charge

$$\vec{F}_{magnetic} = q\vec{v} \times \vec{B}$$

An electron walks into a Corn Field/Magnetic Field.
Which way the force point?

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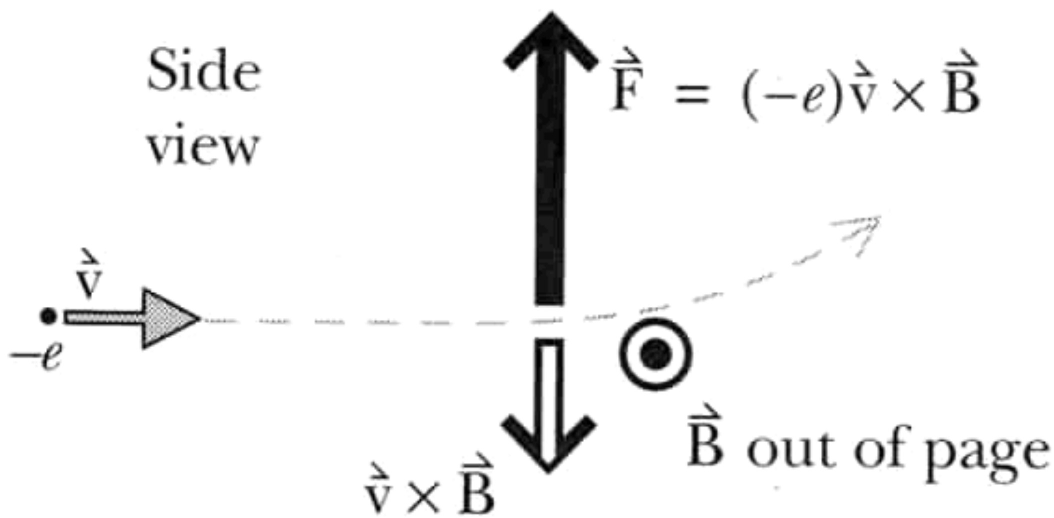
Magnetic Force on a Charge

$$\vec{F}_{magnetic} = q\vec{v} \times \vec{B}$$



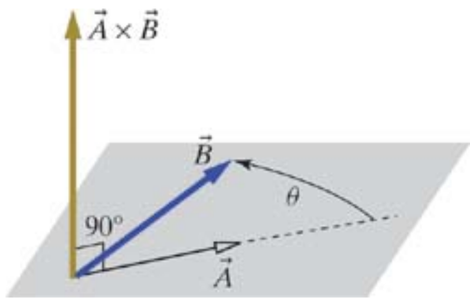
Electron charge = -e:

The magnetic force on a moving electron is in opposite direction to the direction of the cross product $\vec{v} \times \vec{B}$

Right-Hand Rule

$$\vec{F}_{\rm mag} = q\vec{v} \times \vec{B}$$

MAGNETIC FORCE
point charge

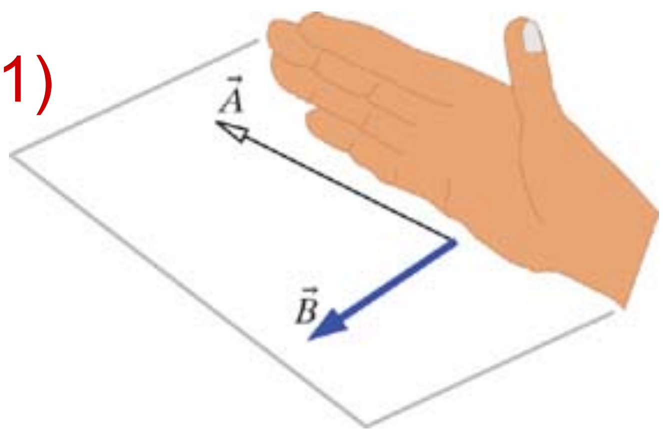


Result of Cross Product $\vec{v} \times \vec{B}$

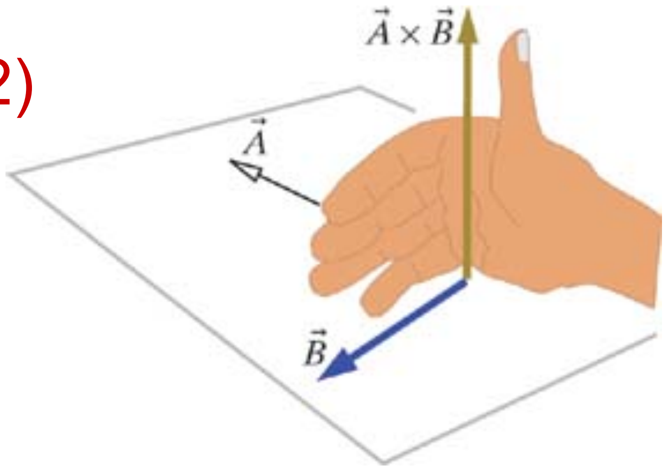
is Perpendicular to both $\vec{v}$ and $\vec{B}$

Right-Hand Rule:

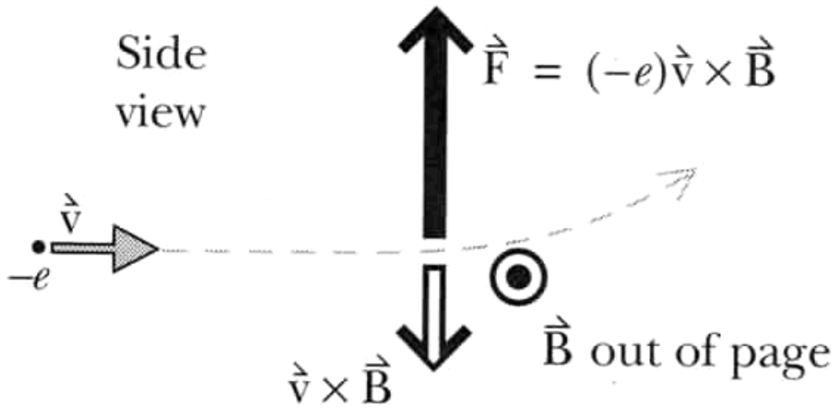
1)



2)



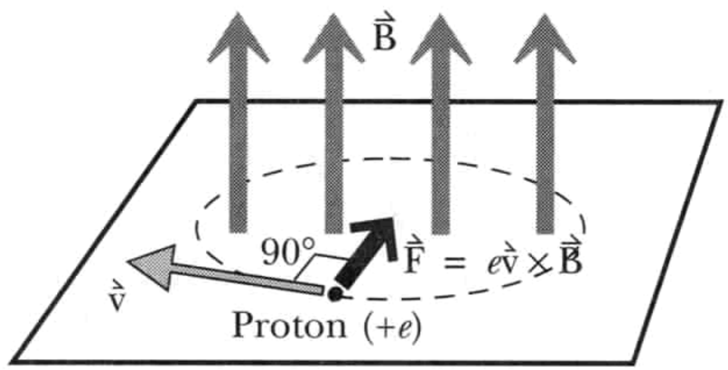
Motion in a Magnetic Field



$$\boxed{\vec{F}_{magnetic} = q\vec{v} \times \vec{B}}$$

What if we have large (infinite) area with constant $\vec{B} \perp \vec{v}$

$$\left|\frac{d\vec{p}}{dt}\right| = qvB$$



http://www.cabrillo.edu/~jmccullough/Applets/OSP/Electricity_and_Magnetism/em_ChargeInBField.jar

Determining the Momentum of a Particle

Position vector r: $\left|\dfrac{d\vec{r}}{dt}\right| = v = \omega r \longrightarrow \omega = \dfrac{v}{r}$ Circular motion

$$\left|\frac{d\vec{p}}{dt}\right| = \omega p = \left(\frac{v}{r}\right)p \qquad \left|\frac{d\vec{p}}{dt}\right| = |q|vB$$

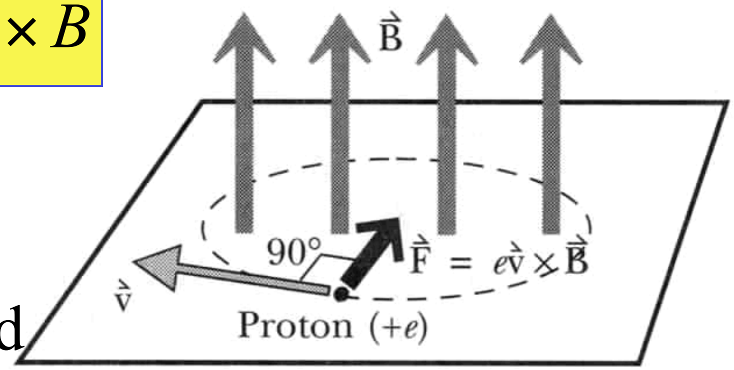
$$\left(\frac{v}{r}\right)p = |q|vB$$

$\boxed{p = |q|Br}$ $\longleftarrow$ valid even for relativistic speeds

Used to measure momentum in high-energy particle experiments

Circular Motion at any Speed

$$\boxed{\vec{F}_{magnetic} = q\vec{v} \times \vec{B}}$$



Any rotating vector:

$$\left|\frac{d\vec{X}}{dt}\right| = \omega\left|\vec{X}\right|$$ ω…angular speed

$$\left|\frac{d\vec{p}}{dt}\right| = \omega\left|p\right|$$

$$\left|\frac{d\vec{p}}{dt}\right| = \left|q\vec{v} \times \vec{B}\right| = \left|q\right| vB \sin 90^o$$

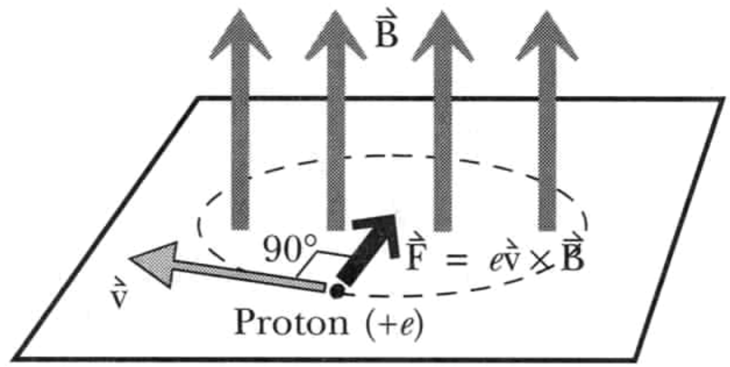
$$\omega \frac{mv}{\sqrt{1 - v^2/c^2}} = \left|q\right| vB$$

$$\boxed{\omega = \frac{\left|q\right| B}{m}\sqrt{1 - v^2/c^2}}$$

Cyclotron Frequency

Circular Motion at Low Speed

$$\omega = \frac{|q|B}{m}\sqrt{1 - v^2 / c^2}$$



if $v << c$: $\boxed{\omega = \frac{|q|B}{m}}$

independent of v!

Alternative derivation:

$$F = ma$$

$$|q| vB \sin 90^\circ = m\frac{v^2}{R}$$

$$|q|B = m\omega \longrightarrow \boxed{\omega = \frac{|q|B}{m}}$$

Circular motion:

$$a = \frac{v^2}{R} \qquad \omega = \frac{v}{R}$$

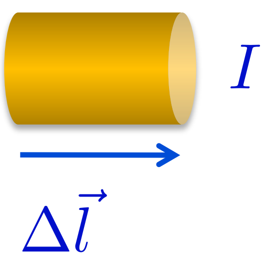
Period T: $\omega = \frac{2\pi}{T} \longrightarrow \boxed{T = 2\pi\frac{m}{|q|B}} \longleftarrow$ Non-Relativistic

Biot-Savart Law

$$\vec{B} = \left(\frac{\mu_o}{4\pi}\right)\frac{q\vec{v} \times \hat{r}}{|r|^2}$$

BIOT-SAVART LAW
point charge

We need to understand how these are related



$$\vec{B} = \left(\frac{\mu_o}{4\pi}\right)\frac{I\Delta\vec{l} \times \hat{r}}{|r|^2}$$

BIOT-SAVART LAW
current in a wire

$\Delta\vec{l}$ = length of this chunk of wire

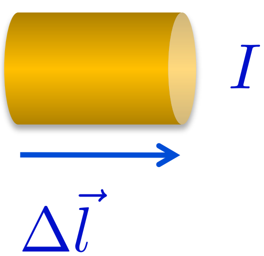
Blast from the Past:
Lecture 12

Magnetic Force on a charge or wire

$$\vec{F}_{\mathrm{mag}} = q\vec{v} \times \vec{B}$$

MAGNETIC FORCE
point charge

We need to understand how these are related



$$\Delta\vec{F}_{\mathrm{mag}} = I\Delta\vec{l} \times \vec{B}$$

MAGNETIC FORCE
current in a wire

$\Delta\vec{l}$ = length of this chunk of wire

GOAL: Show $q\vec{v} \longrightarrow I\Delta\vec{l}$

(point charge) (wire)

(POSITIVE) POINT CHARGE

q $\vec{v}$

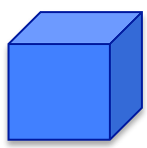
$q\vec{v}$

$q\vec{v}$

MANY POINT CHARGES

N particles

$N q\vec{v}$



$n = \left[\frac{\#}{m^3}\right]$ particles per volume ΔV

ΔV

$(n\Delta V) q\vec{v}$

CHUNK OF WIRE

I

$\Delta\vec{l}$ = length of this chunk of wire

Move the vector symbol

$$q\vec{v} n\Delta V = q\vec{v} nA\Delta l$$

$$= \underbrace{q|v|nA}_{\equiv I}\Delta\vec{l} \qquad I\Delta\vec{l}$$

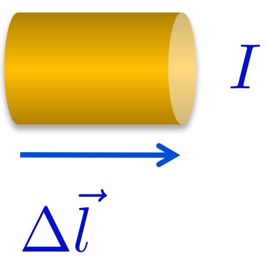
Blast from the Past: Lecture 12

Magnetic Force on a charge or wire

$$\vec{F}_{\text{mag}} = q\vec{v} \times \vec{B}$$

MAGNETIC FORCE
point charge

We just showed how these are related



$$\boxed{\Delta\vec{F}_{\text{mag}} = I\Delta\vec{l} \times \vec{B}}$$

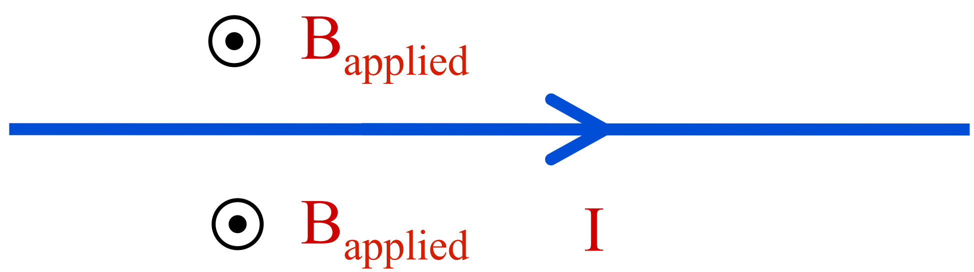
MAGNETIC FORCE
current in a wire

$\Delta\vec{l}$ = length of this chunk of wire

Magnetic Force on a Wire

$$\Delta\vec{F}_{\mathrm{mag}} = I\Delta\vec{l} \times \vec{B}$$

Current-carrying wire in an applied magnetic field B

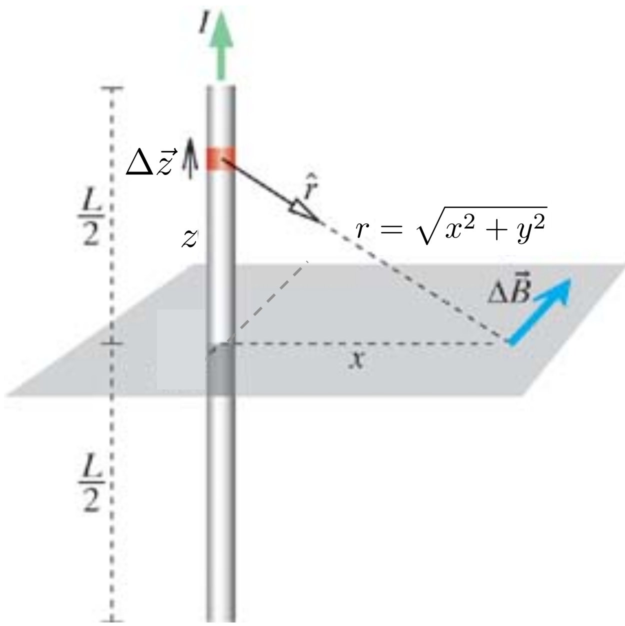


Which way will the wire move?

Magnetic Field of a Straight Wire

$$|B_z| = \left(\frac{\mu_o}{4\pi}\right)\frac{IL}{x\sqrt{x^2+(L/2)^2}}$$

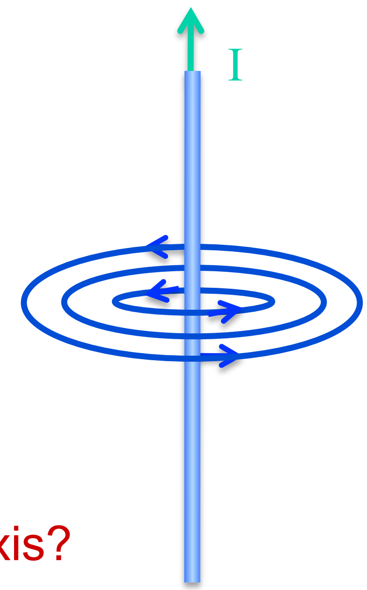
B in the bisecting plane



Which direction does B point?

→ Always along concentric circles

In cylindrical coordinates, it points in the " $\hat{\theta}$ " direction



Will the y axis look different from the x axis?

No, so we can trade x → r

$$\boxed{\vec{B} = \left(\frac{\mu_o}{4\pi}\right)\frac{IL}{r\sqrt{r^2+(L/2)^2}}\hat{\theta}}$$

B of a Long Straight Wire
(cylindrical coord.)

Blast from the Past:
Lecture 13

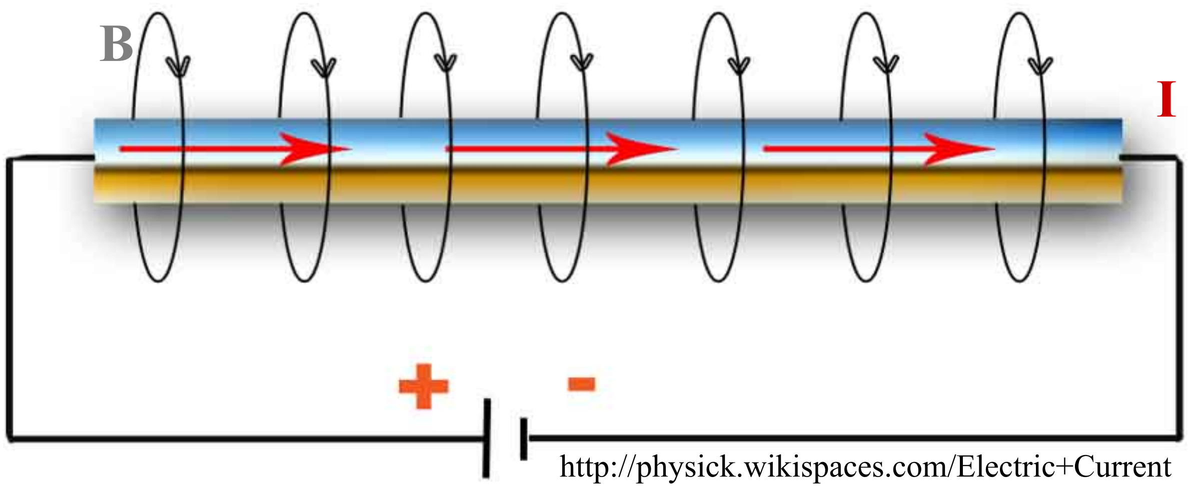
Very Close to the Wire

$$\vec{B} = \left(\frac{\mu_o}{4\pi}\right)\frac{IL}{r\sqrt{r^2+(L/2)^2}}\hat{\theta}$$

Very close to the wire: r << L $\quad \sqrt{r^2+(L/2)^2} \approx L/2$

$$\Rightarrow \vec{B} = \left(\frac{\mu_o}{4\pi}\right)\frac{IL}{r(L/2)}\hat{\theta} = \boxed{\left(\frac{\mu_o}{4\pi}\right)\frac{2I}{r}\hat{\theta} = \vec{B}}$$

CLOSE TO THE WIRE



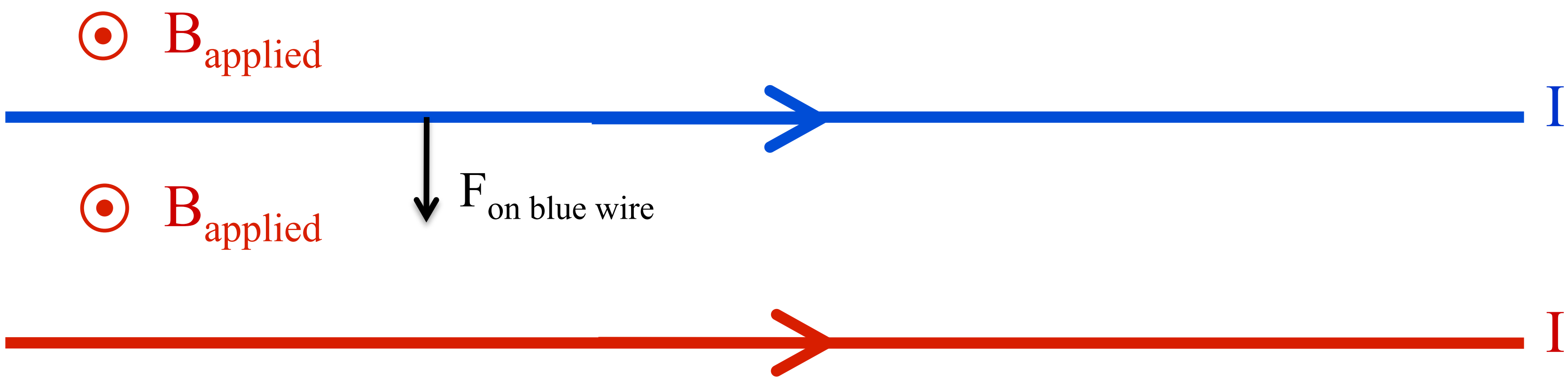
http://physick.wikispaces.com/Electric+Current

Blast from the Past: Lecture 13

Force Between Parallel Wires

$$\Delta\vec{F}_{\mathrm{mag}} = I\Delta\vec{l} \times \vec{B} \qquad\qquad \vec{B} = \left(\frac{\mu_o}{4\pi}\right)\frac{2I}{x}\hat{\theta}$$

B_{applied} = Magnetic field applied by the **red** wire.   **Blue** wire feels a force down.

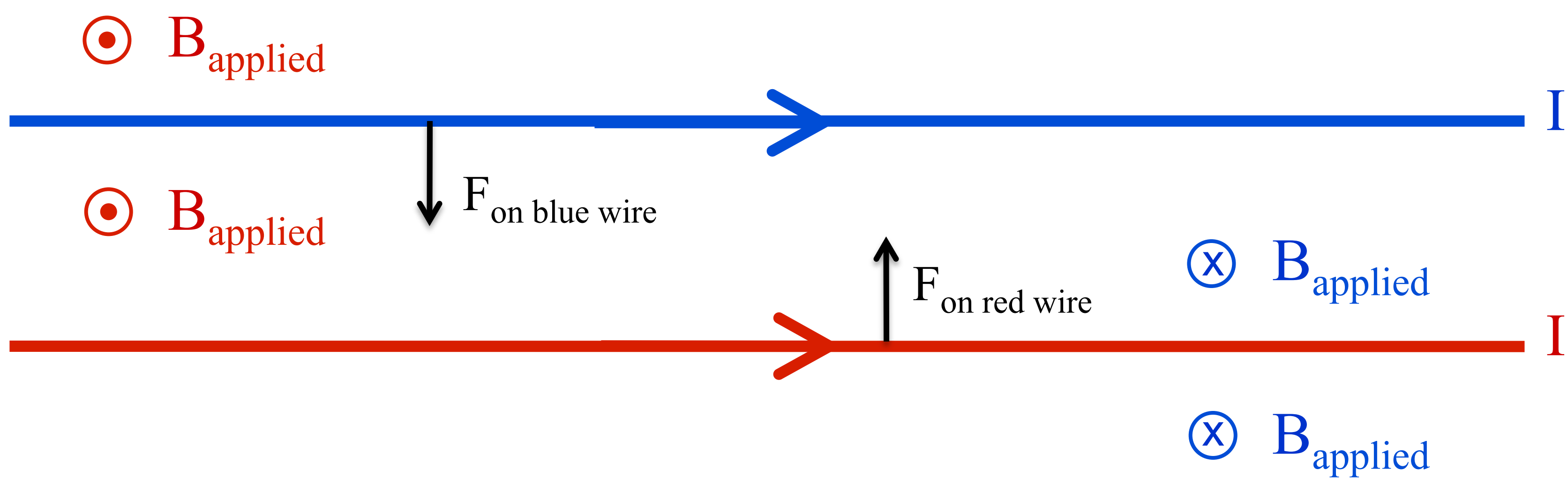


What about reciprocity? (Equal and opposite forces)

Force Between Parallel Wires

$$\Delta \vec{F}_{\text{mag}} = I \Delta \vec{l} \times \vec{B} \qquad\qquad \vec{B} = \left(\frac{\mu_o}{4\pi}\right) \frac{2I}{x} \hat{\theta}$$

B_{applied} = Magnetic field applied by the **red** wire. **Blue** wire feels a force down.

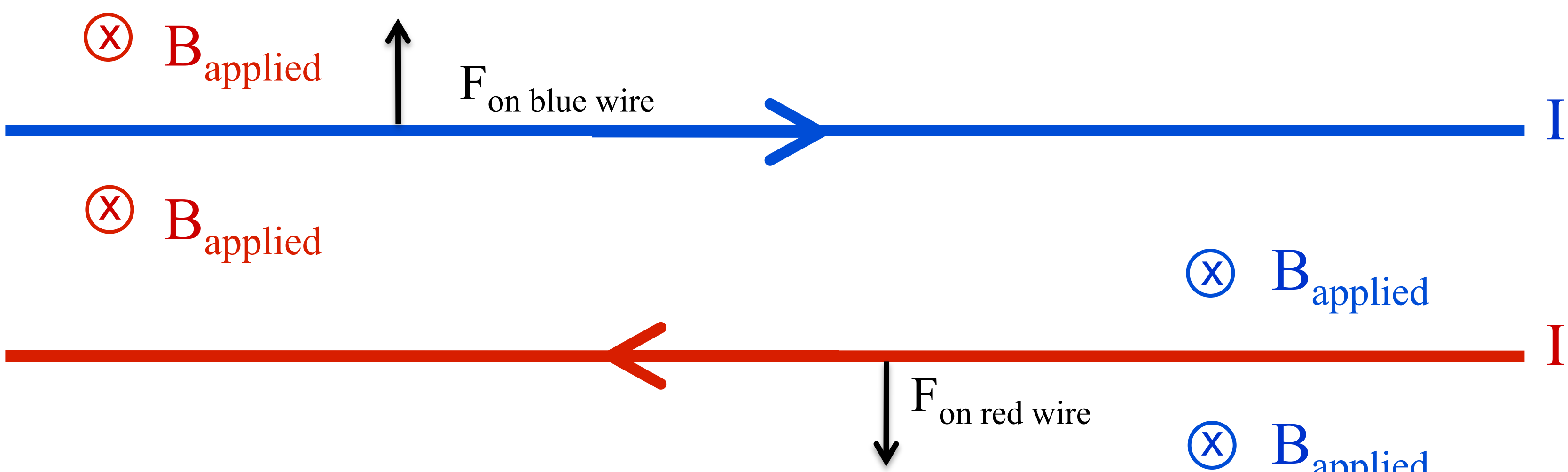


B_{applied} = Magnetic field applied by the **blue** wire. **Red** wire feels a force up.

Force Between (Anti) Parallel Wires

$$\Delta\vec{F}_{\text{mag}} = I\Delta\vec{l} \times \vec{B} \qquad \vec{B} = \left(\frac{\mu_o}{4\pi}\right)\frac{2I}{x}\hat{\theta}$$

B_{applied} = Magnetic field applied by the **red** wire. **Blue** wire feels a force up.



B_{applied} = Magnetic field applied by the **blue** wire. **Red** wire feels a force down.

Hall Effect

By measuring the Hall effect for a particular material,
we can determine the sign of the moving particles
that make up the current

Why would it be anything other than electrons? (Negative charges)

Semiconductors: sometimes current is carried by electrons,
but sometimes it is carried by the "holes".

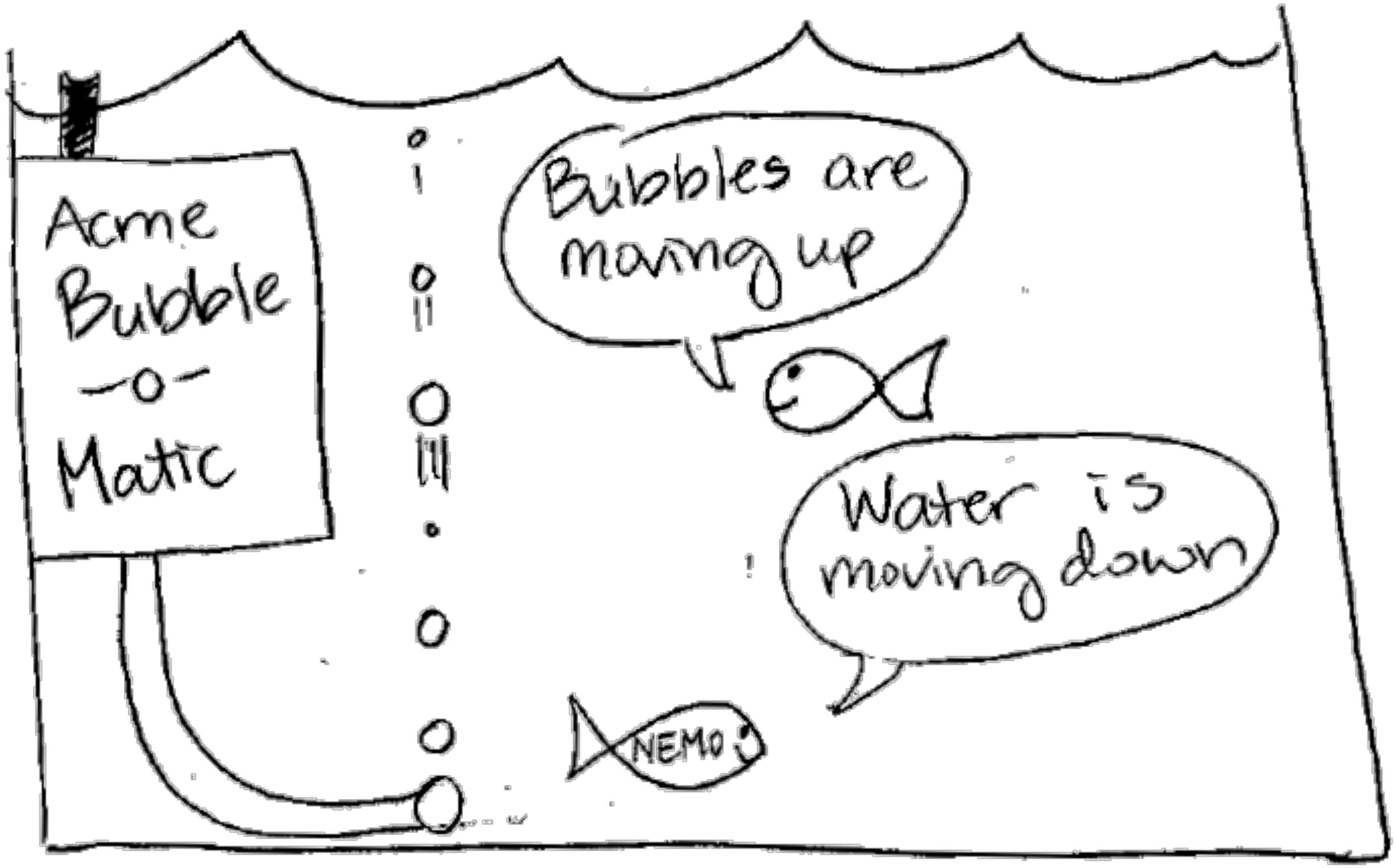
In **semiconductors**, "holes" (missing electrons)
in the electron sea behave like positive charges.

ZEN KOAN

<u>Water from a hose</u>

Zen riddle: Is water coming out of the hose, or is the absence of water moving into the hose?

"Holes" not useful here

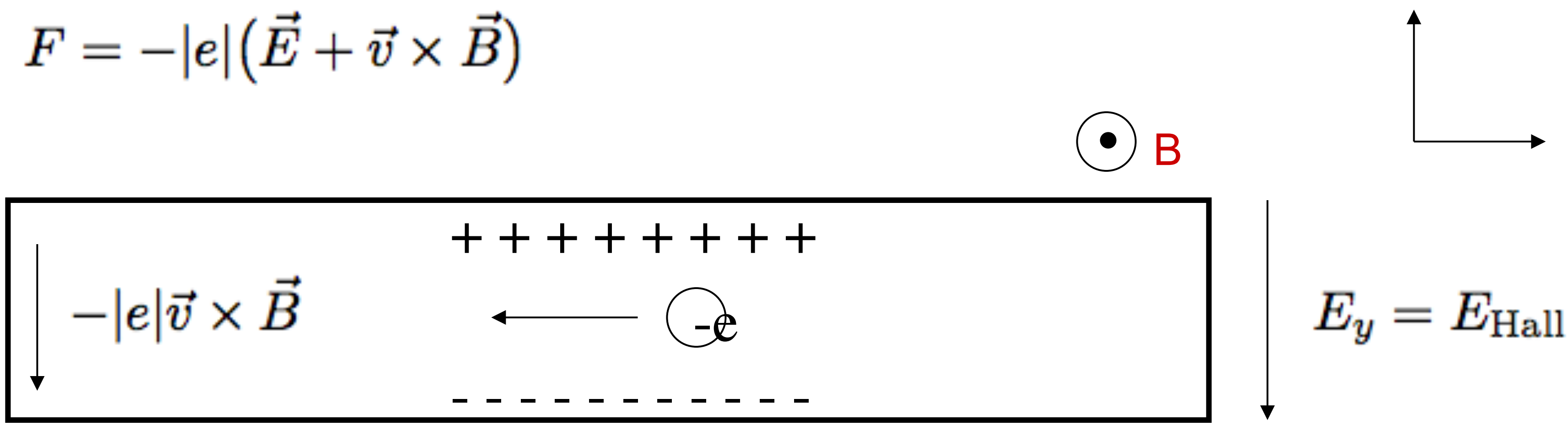


"Holes" useful here

In a semiconductor, "Holes" in the electron sea act like positive charges.

Hall Effect and Electrons

$$F = -|e|\left(\vec{E} + \vec{v} \times \vec{B}\right)$$



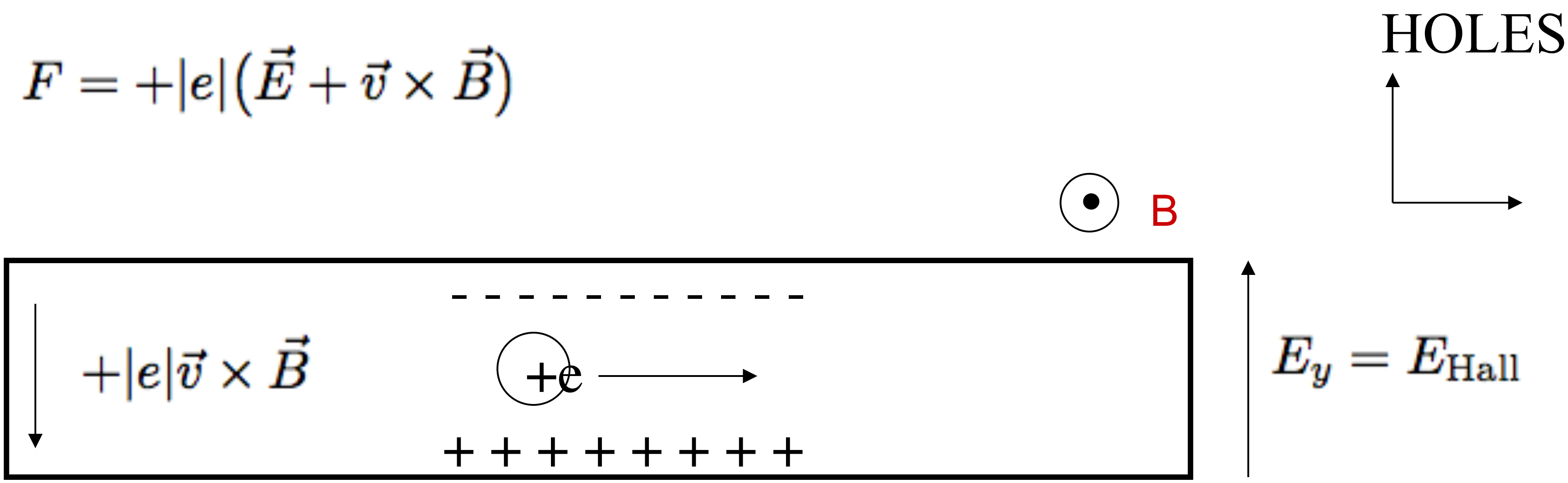
$$\Rightarrow \qquad E_y = E_{\text{Hall}}$$

E_{Hall} points down

due to buildup of charge.

Hall Effect and Holes

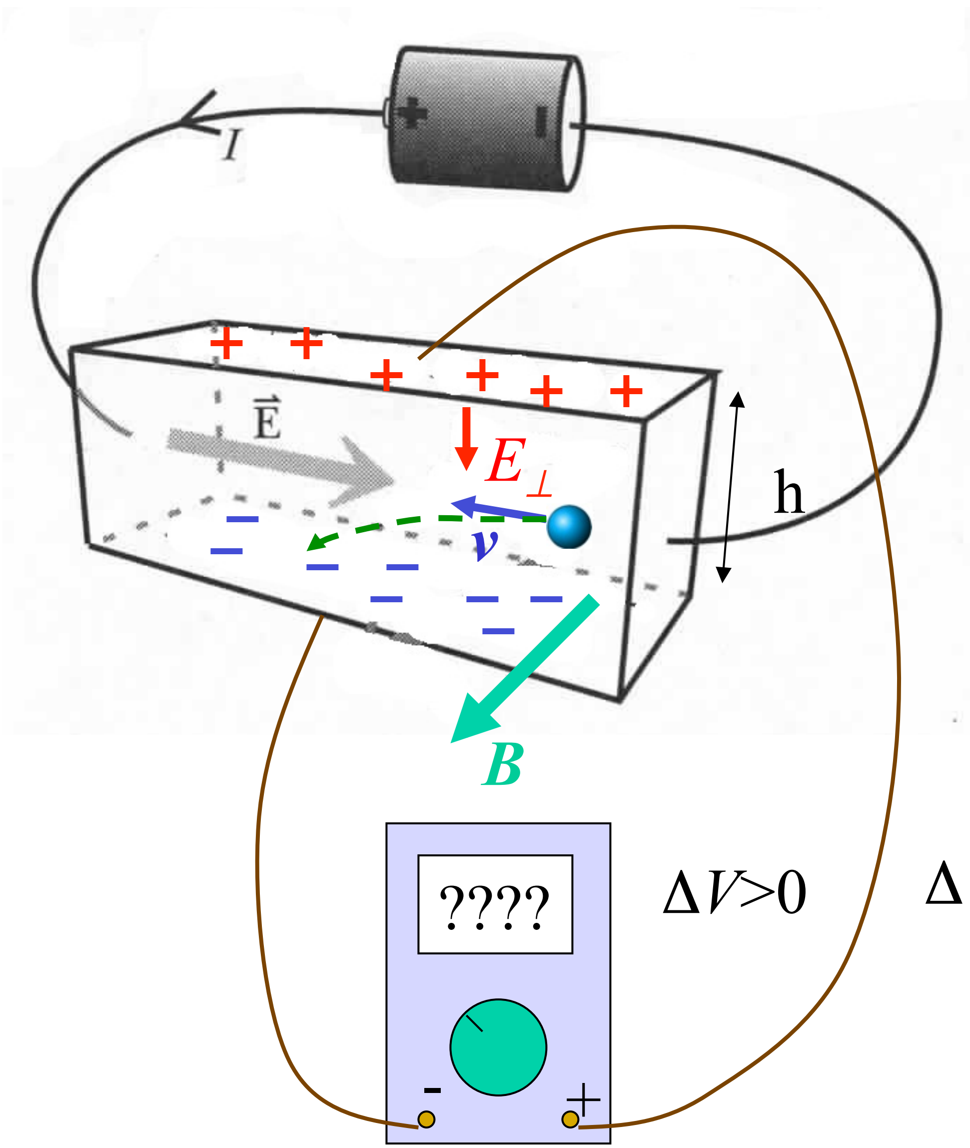
$$F = +|e|(\vec{E} + \vec{v} \times \vec{B})$$



$E_y = E_{\text{Hall}}$

E_{Hall} points up due to buildup of charge.

Hall Effect



$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

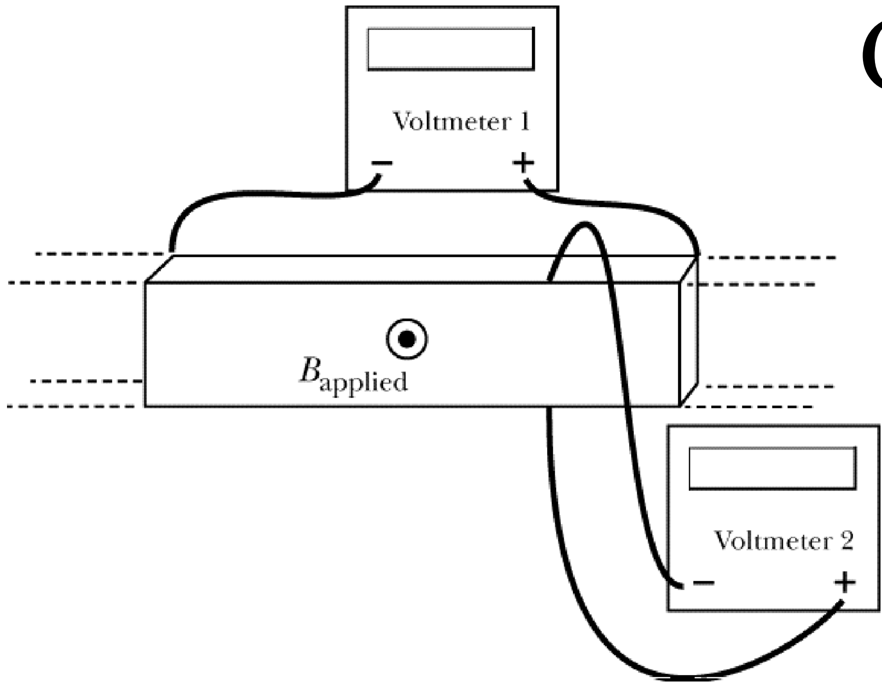
$$\vec{F}_{e\perp} + \vec{F}_B = 0$$

$$e\vec{E}_{e\perp} = -e\vec{v} \times \vec{B}$$

$$E_{e\perp} = \bar{v}B$$

$$\Delta V = E_{e\perp}h = \bar{v}Bh$$

Clicker Question



Voltmeter 1 reading is POSITIVE
Voltmeter 2 reading is POSITIVE

Mobile charges are:

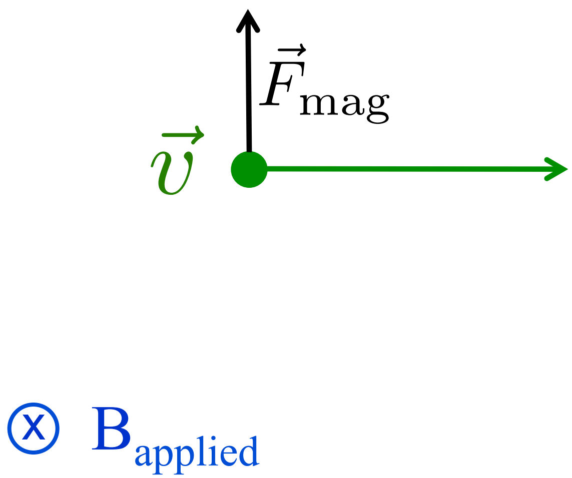
A) Positive (holes)
B) Negative (electrons)
C) Not enough information

iClicker

$$\vec{F}_{\mathrm{mag}} = q\vec{v} \times \vec{B}$$

MAGNETIC FORCE
point charge

Proton



In which direction does **F_{mag}** point for the **proton**?

A) Up

B) Down

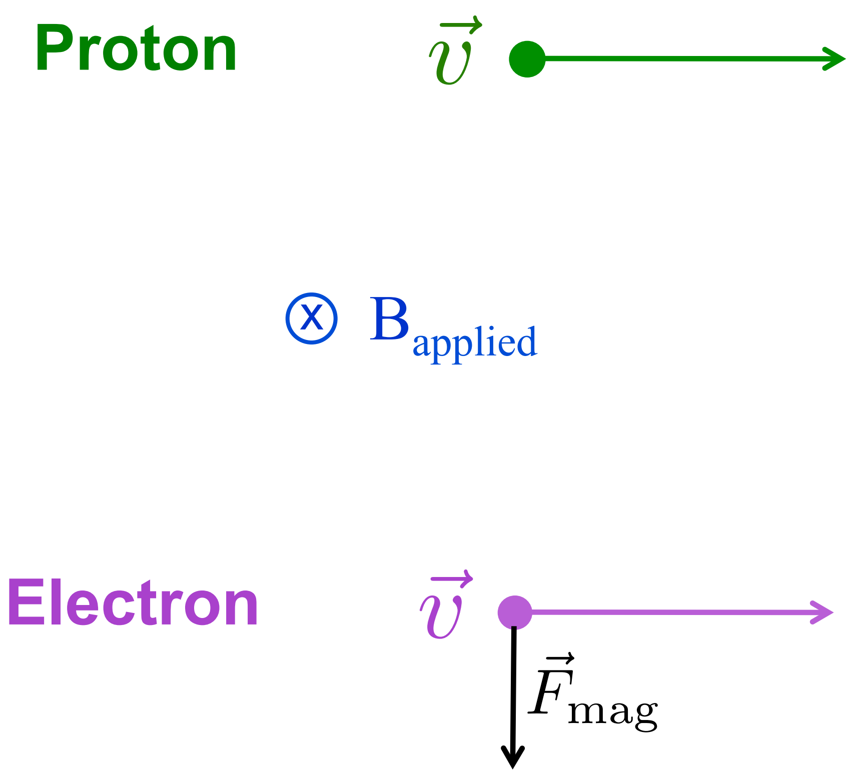
C) Into the Board

D) Out of the Board

iClicker

$$\vec{F}_{\mathrm{mag}} = q\vec{v} \times \vec{B}$$

MAGNETIC FORCE
point charge



A) Up

B) Down

C) Into the Board

D) Out of the Board

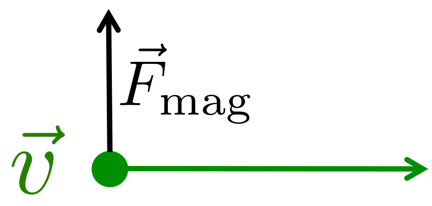
In which direction does $\mathbf{F}_{\mathbf{mag}}$ point for the **electron**?

Hall Effect

$$\vec{F}_{\mathrm{mag}} = q\vec{v} \times \vec{B}$$

MAGNETIC FORCE
point charge

A **hole** in the electron sea behaves like a **proton**.



Proton or "Hole"

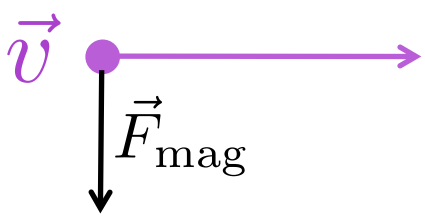
Inside a Material:

Moving **holes** get pushed to the top

⊗ $\mathrm{B}_{\mathrm{applied}}$

⊗ $\mathrm{B}_{\mathrm{applied}}$

Electron



Moving **electrons** get pushed to the bottom

Hall Effect

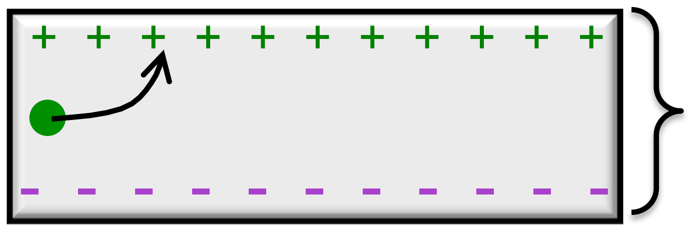
$\vec{F}_{\mathrm{mag}} = q\vec{v} \times \vec{B}$

MAGNETIC FORCE
point charge

A **hole** in the electron sea behaves like a **proton**.

Inside a Material:

Moving **holes** get pushed to the top



ΔV = Hall Voltage

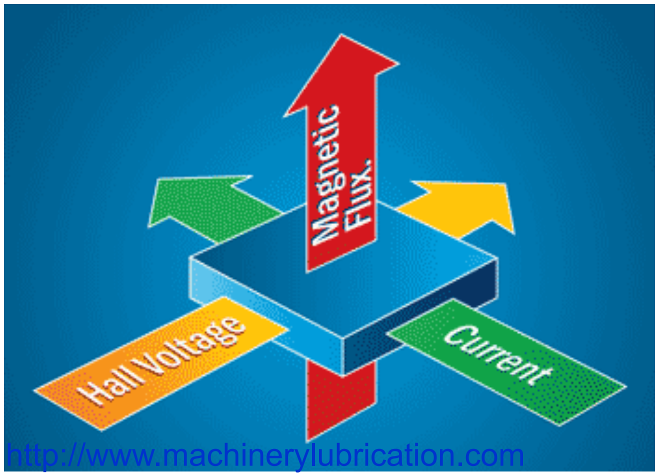
How long does this go on?
→ Until the Hall Voltage is strong enough to balance the magnetic force $\vec{F}_{\mathrm{mag}}$

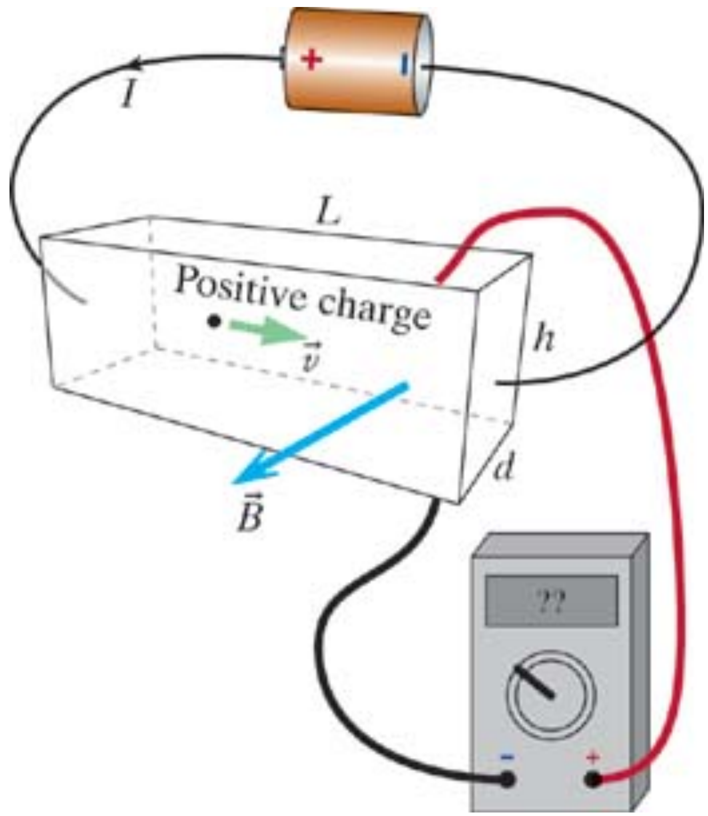
⊗ B_{applied}

Moving **electrons** get pushed to the bottom

ΔV = Hall Voltage

Measuring the Hall Effect





1. Apply B-Field
2. Apply Current I
3. Measure "Hall Voltage"